Production of light nuclei, hypernuclei and their antiparticles in relativistic nuclear collisions

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Abstract

We present, using the statistical model, an analysis of the production of light nuclei, hypernuclei and their antiparticles in central collisions of heavy nuclei. Based on these studies we provide predictions for the production yields of multiply-strange light nuclei.

1 Introduction

One of the major goals of ultrarelativistic nuclear collision studies is to obtain information on the QCD phase diagram [1]. Currently, one of the most direct approaches is the investigation of hadron production. Hadron yields measured in central heavy ion collisions from AGS up to RHIC energies can be described very well [2,3,4,5,7,8,9,10,11,12] within a hadro-chemical equilibrium model. In our approach [2,4,7,12,13,14] the only parameters are the chemical freeze-out temperature T and the baryo-chemical potential μ_b (and the fireball volume V, in case yields rather than ratios of yields are fitted). Other approaches [6,9,11,15,16] employ (several) other, non-thermal, parameters. For a review see [17].

The main result of these investigations was that the extracted temperature values rise rather sharply from low energies on towards $\sqrt{s_{NN}} \simeq$10 GeV and reach afterwards constant values near T=160 MeV, while the baryochemical potential decreases smoothly as a function of energy. This limiting temperature [18] behavior suggests a connection to the phase boundary and it was, indeed, argued [19] that the quark-hadron phase transition drives the equilibration dynamically, at least for SPS energies and above. For the lower energies, the quarkyonic state of matter [20] could complement this picture by providing a new phase boundary at large μ_b values. The conjecture of the tricritical point [21] was put forward in this context.

The importance of measurements at very high energies to obtain information on the existence of a limiting temperature of excited hadronic matter produced in nuclear collisions was pointed out early [22,23,24,25] based on analysis of particle spectra at the Bevalac (see also the review [26]), from pions to heavier complex nuclei.

At first glance, it may seem inappropriate to use the chemical freeze-out concept for light nuclei, as their binding energies are a few MeV, much less than the chemical freeze-out temperatures of 100-170 MeV. We note, however, that the relative yield of particles composed of nucleons is determined by the entropy per baryon, which is fixed at chemical freeze-out. This has been first recognized already 30 years back [22] and was subsequently further substantiated in [25], constituting the basis of thermal analyses of yields of light nuclei [27,28]. It is entropy conservation, and not the difference between the binding energy and temperature of the system, which governs the production yields in this case After chemical freeze-out, entropy is conserved.

It was also noted then that the yields obtained within the thermal model are in close agreement to those from coalescence models [27,29]. The thermal model studies were already at that time extended to nuclei carrying strangeness (hyperons in replacement of nucleons) and even hypothetical objects with roughly equal number of up, down and strange quarks (strangelets). At the same time, a vigorous line of theoretical investigations on the existence of multi-strange hypernuclei, or MEMOs [30,31,32,33] was established.

Recently, the first measurement of the lightest (anti)hypernucleus, (anti)hyper-tritium, in high-energy nucleus-nucleus collisions was achieved by the STAR experiment at the RHIC [34]. This measurement opens up a very interesting new regime for tests of particle production at chemical equilibrium. At relatively low beam energies, where the baryo-chemical potential and, hence, the baryon density is maximum (FAIR energy regime) objects with a large number of baryons and moderate strangeness may be abundantly produced [33]. At RHIC and LHC energies production of objects with moderate (anti)baryon number and large strangeness content may be expected. In this paper we investigate and predict within the thermal model the production yields of heavy baryons and anti-baryons and in particular of hypernuclei and their antiparticles and confront these calculations with all presently available data ranging from AGS to RHIC energies.

2 Preliminaries

The measurement of the production yields of light nuclei (and anti-nuclei) without strangeness in central nuclear collisions provides significant constraints on thermal model parameters, in particular on the value of the baryo-chemical potential μ_b. This is most easily seen when one recognizes that yield ratios such as ${}^{n}\bar{H}e/{}^{n}He$ scale like $\exp\left[-(2n\mu_b/T)\right]$. In Fig. 1 we show the updated thermal fit to the hadron yield data measured at RHIC ($\sqrt{s_{NN}}$=200 GeV) including the newly-measured [34] yield ratio ${}^{3}\bar{H}e/{}^{3}He$. Including this ratio significantly narrows the range of possible μ_b values, while T and V of the new fit remain unchanged (T=164 MeV, V=1960 fm^3) compared to our earlier fit [13]. Quantitatively, the new fit leads to μ_b=24±2 MeV, while without the ratio ${}^{3}\bar{H}e/{}^{3}He$, μ_b=30±4 MeV [13]. The quality of the present fit is similar to that of the earlier one (which had χ^2/dof=29.7/12). This result supports previous findings at lower energies [27,28,29]. We

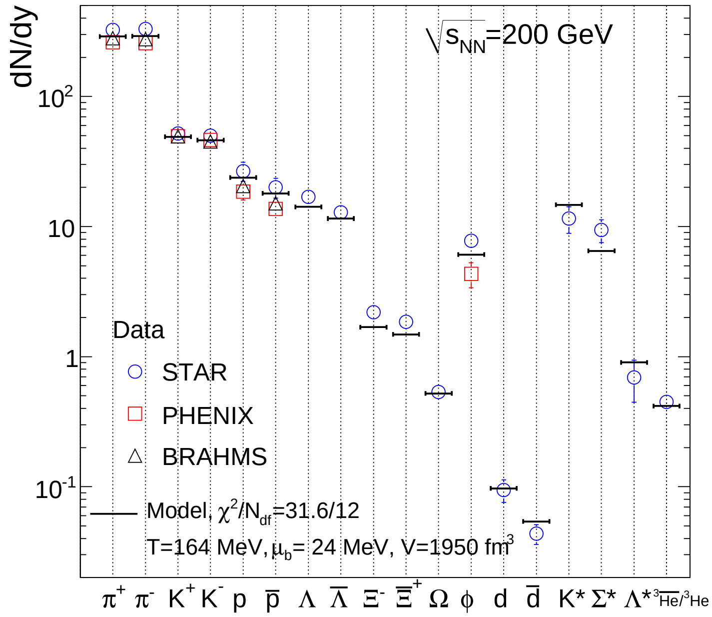

Figure 1. Hadron yields in comparison with the thermal model fit of combined data (excluding K^*, Σ^*, Λ^*), for the RHIC energy of $\sqrt{s_{NN}}$=200 GeV. The ratio $^3\bar{He}/^3He$, recently measured by the STAR experiment [34] is included in the fit.

stress that the agreement between the experimental value and the calculated one for the ratio $^3\bar{H}e/^3He$ is a powerful argument that indeed entropy conservation governs the production of light nuclei. If one were to use a temperature comparable to the binding energy per nucleon, that is T=5 MeV, the calculated ratio would be $3.1{\cdot}10^{-13}$, while it is 0.415 for T=164 MeV, see Fig. 1.

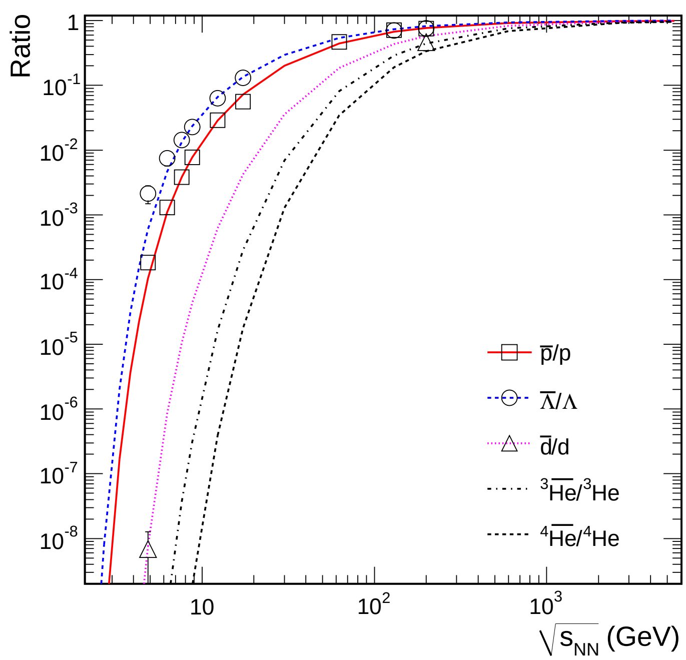

Figure 2. Energy dependence of anti-baryon to baryon yield ratios. The lines are thermal model results as described in the text. The symbols represent measured data.

In Fig. 2 we show that predictions using the thermal model can be used to describe quantitatively the measured energy dependence of $\bar{p}/p$, $\bar{d}/d$, and $\bar{\Lambda}/\Lambda$ yield ratios over a

very wide energy range The calculations, here and in the following, are performed using the parametrizations for T and μ_b established in [13] based on fits of midrapidity data in central collisions. The penalty against anti-particles at lower energies, well described within the thermal approach, is also drastically exhibited in this figure. Note, in particular, the very good agreement between the model and the measurements at AGS [35] for the $\bar{d}/d$ ratio, which extends the the range of the model agreement over 8 orders or magnitude (for the other measurements see references in [12,13]). It is thus natural to extend such analyses to light nuclei containing strangeness. Note that, at the lowest energies, the canonical strangeness suppression is important and is incorporated in our model as described in [12]. In the following we will therefore use the thermal model with the parameters as discussed to analyze the production of hypernuclei and their anti-particles and confront model predictions with the now available data.

3 Production of Hypernuclei at RHIC Energy

In Table 1 we show a comparison of the measured data [34] and model calculations for the best fit thermal parameters discussed above. The yield ratio ${}^3_{\bar{\Lambda}}\bar{H}/{}^3_{\Lambda}H$ is as well reproduced by the model as the ratio ${}^3\bar{H}e/{}^3He$. On the other hand, the measured ratios of (anti)hyper-tritium to (anti)${}^3He$ are larger than predicted in the model by about two standard deviations, using the statistical and systematic uncertainties quoted for the data.

Table 1

Ratios at RHIC energy, $\sqrt{s_{NN}}$=200 GeV. The experimental values are from the STAR experiment [34] and contain statistical ans systematic errors. The errors for the model calculations correspond to the errors of the fit for the baryochemical potential, $\mu_b = 24 \pm 2$ MeV.

Ratio	Experiment	Model
${}^3\bar{H}e/{}^3He$	0.45±0.02±0.04	0.42±0.03
${}^3_{\bar{\Lambda}}\bar{H}/{}^3_{\Lambda}H$	0.49±0.18±0.07	0.45±0.03
${}^3_{\Lambda}H/{}^3He$	0.82±0.16±0.12	0.35±0.003
${}^3_{\bar{\Lambda}}\bar{H}/{}^3\bar{H}e$	0.89±0.28±0.13	0.37±0.003

To shed more light on the situation we turn now to the energy dependence of (strange) baryon production. In Fig. 3 we show the experimental energy dependence of the Λ/p and d/p ratios and confront these data with our thermal model predictions. The degree of agreement between data and calculations is impressive. We also include in this figure thermal model predictions for the energy dependence of the ratio ${}^3_{\Lambda}H/{}^3He$ and ${}^3_{\bar{\Lambda}}\bar{H}/{}^3\bar{H}e$. The broad maximum around $\sqrt{s_{NN}}\simeq$5 GeV for the ratio ${}^3_{\bar{\Lambda}}\bar{H}/{}^3\bar{H}e$ has the same origin as the maximum in the K^+/π^+ ratio, namely it arises as a consequence of strangeness neutrality condition, imposed in our model, and a competition between rising T and decreasing μ_b [13]. We also note that a slightly less prominent maximum is likely to survive even if one relaxes the condition of strangeness neutrality, as demonstrated in [33]. At high energies the value for the two ratios approach each other, as expected for decreasing values of μ_b at a nearly constant temperature.

In Fig. 4 we show the measured energy dependence for the ${}^3He/{}^3H$ and the ${}^3_{\Lambda}H/({}^3He(\Lambda/p))$ ratio. This double ratio was suggested by the authors of [34] in the expectation that dividing out the strange to non-strange baryon yield should result in a

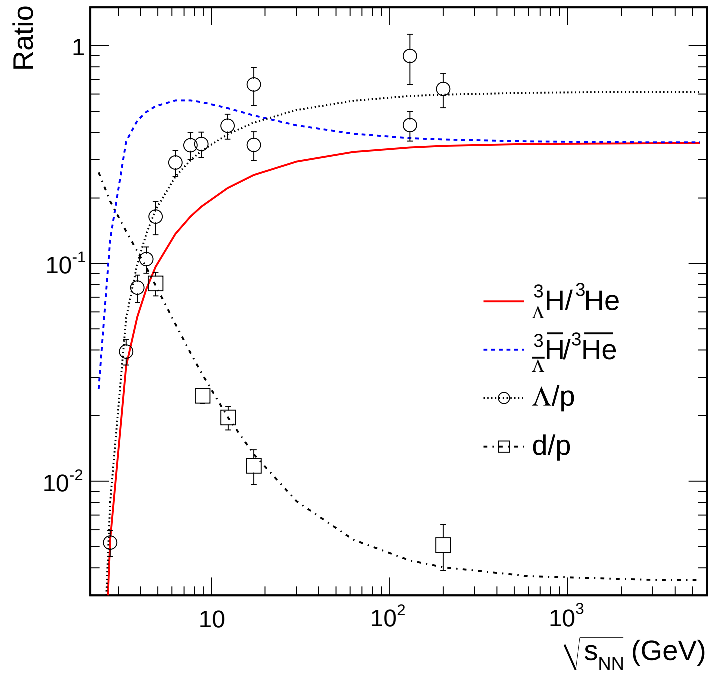

Figure 3. Energy dependence of various baryon yield ratios. The lines are calculations, the symbols are experimental data.

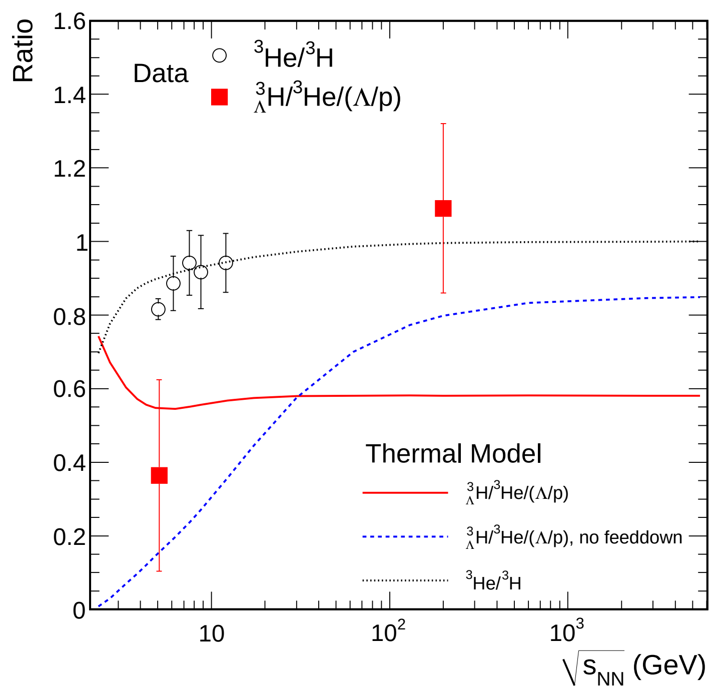

Figure 4. Energy dependence of nuclei and hypernuclei production ratios. The data points are extracted from ref. [34], the lines are our model calculations. Note the discrepancy between data and model for the double ratio involving hyper-tritium, where the continuous line represents the physical case, while the dashed line represents the case without the important contribution from feed-down from strong decays on the Λ/p ratio (see text).

value near unity. The data are compared to thermal model predictions. Note that there is negligible feed-down from heavier states into states with baryon number 3. As expected, the measured energy dependence of the $^3He/^3H$ is well reproduced by the model calculations. On the other hand, the discrepancy between thermal model predictions and data

for the ${}^3_\Lambda H/({}^3He(\Lambda/p))$ ratio is apparent (red line). It is important to realize that the ratio Λ/p is significantly influenced by feed-down from strong decays of excited baryonic states, leading to a value for the double ratio significantly below unity. The red line in Fig. 4 contains such feed-down, the blue dashed line represents a calculation where the feeding is artificially left out. The feed-down from strong decays increases the Λ/p ratio and, hence, reduces the overall ratio. The STAR collaboration actually measures a ratio close to 1, above the thermal model prediction by twice the error quoted by the experiment. Interestingly, results from the E864 collaboration [36] (as shown in ref. [34]) at AGS energy are, albeit with large uncertainties, consistent with the thermal model prediction. The discrepancy at RHIC energy, if experimentally established, would point to a new production mechanism not contained in the thermal approach and not present at lower beam energies. The possible existence of an excited $J^\pi = 3/2^+$ state of (anti)hyper-tritium has been recently pointed out to us [37]. This excited state could contribute via decay to the ground state, and would lead to close agreement between model and data. Further measurements at RHIC and, very soon, LHC energy are eagerly awaited to shed light on the situation.

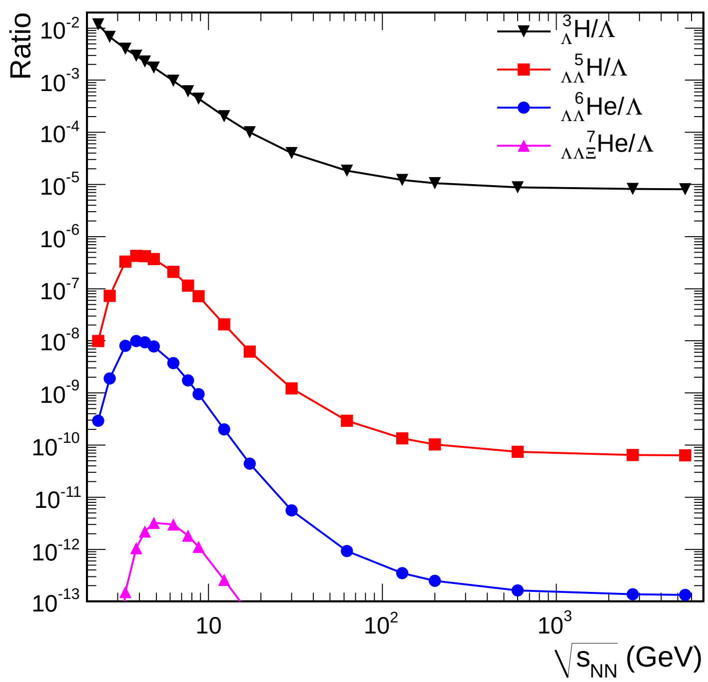

Figure 5. Energy dependence of hypernuclei to Λ yield ratios.

To complete our studies we show, in Fig. 5, predictions within the thermal model for the energy dependence of the production yield of multistrange light hypernuclei [27] relative to Λ hyperons. These ratios exhibit a pronounced maximum in the FAIR energy regime, which is the consequence of a competition between a strong increase (followed by saturation) of T and a strongly decreasing μ_b (see also the discussion above). In addition, the canonical suppression, arising from the condition of local strangeness conservation, leads to reduced yields at low energies. In case of hyper-tritium production, there is no maximum, since it is mainly determined by the strong energy dependence of μ_b at low energies. It is larger at the (low) FAIR energies by two to three orders of magnitude compared to RHIC and LHC energies. Even larger are the differences between low and high energies for the production of the exotic multi-hyperon states.

In Fig. 6 we show, as a function of energy, predictions of yields at midrapidity per one

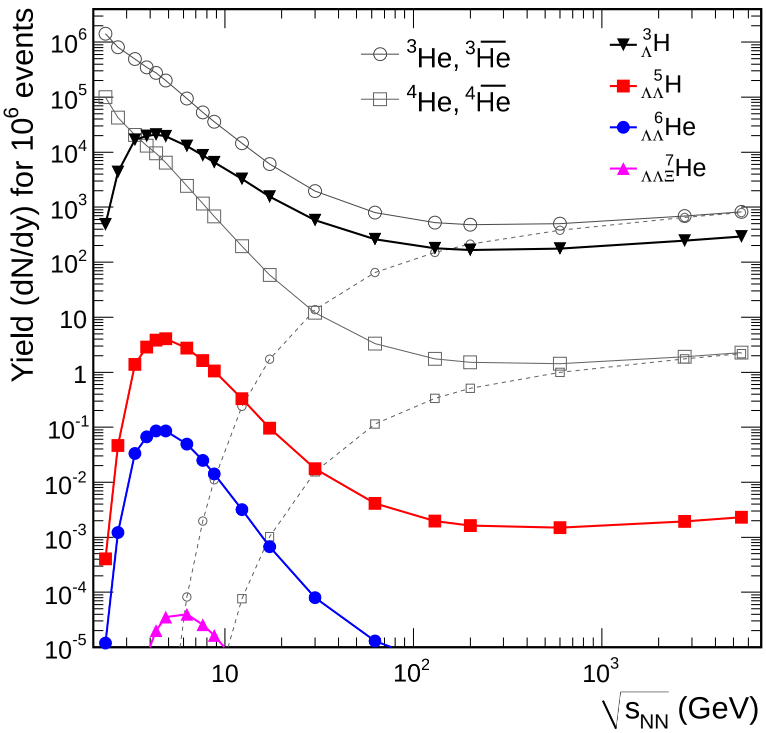

Figure 6. Energy dependence of predicted hypernuclei yields at midrapidity for 10^6 central collisions. The predicted yields of ^3He and ^4He nuclei are included for comparison, along with the corresponding anti-nuclei (dashed lines).

million central collisions. The volume at chemical freeze-out is that from our fits of yields [14]. At FAIR energy the production yields of exotic nuclei is maximal, although the absolute yields are still rather small. As an example, for $^{7}_{\Lambda\Lambda\Xi}He$, the rate of production at 10^6 central Pb+Pb collisions per second is about 60 per month, for a reasonable duty factor of the accelerator. Assuming a reconstruction efficiency of the order of a percent, this implies a few candidates per year of data taking, clearly at the edge of achievability.

At the LHC, (anti-)^{4}He and their corresponding hypernuclei are experimentally accessible. For the LHC energy of 2.76 TeV of the present data taking, we predict ratios ^{3}He/^{4}He and $^3\bar{\text{H}}$e/$^4\bar{\text{H}}$e of $2.76{\cdot}10^{-3}$ and $2.70{\cdot}10^{-3}$, respectively (to be compared to the corresponding values for the RHIC energy of 200 GeV of $3.13{\cdot}10^{-3}$ and $2.37{\cdot}10^{-3}$). These predictions can also be used as guideline for expectation in pp collisions at LHC energy, where one could estimate, in the grand-canonical limit, yields reduced by a factor of the order of 200-400 compared to Pb+Pb collisions. This is compensated by the much larger number of pp collisions (about 10^9 events) which can be inspected at LHC (for a running time of 10^7 s per year of operation). This should allow, at the LHC, a measurement of the yields of produced (anti-)hypernuclei up to mass number 4 in pp and Pb-Pb collisions and provide a detailed test of our predictions.

4 Conclusions

We have demonstrated that the yield of light nuclei and their anti-particles are well reproduced with thermal model calculations employing parameters established from the

analysis of general hadron production in relativistic nuclear collisions. As shown above, such ratios can be used to provide a precision constraint of the baryo-chemical potential μ_b. We have furthermore shown that the newly measured yield ratio ${}^3_\Lambda\bar{H}/{}^3_\Lambda H$ is also well described with the thermal approach, while the ratio ${}^3_\Lambda H/{}^3He$ which is reproduced at AGS energy is significantly underpredicted at RHIC energy. The origin of this discrepancy is currently not clear and needs further study.

Our studies have also indicated interesting energy dependence in such yields and ratios. In particular, particles with large baryon number and moderate strangeness are produced in significant numbers at FAIR energy.

The hyper-nuclei program, started by the STAR experiment at RHIC, has made these studies very topical. Although significant questions remain, it is clear that the study of the production of complex nuclei with and without strangeness in relativistic nuclear collisions can open a new chapter in the quest to understand the relation of particle production to the QCD phase boundary. The thermal model predictions can hopefully soon be tested also at the LHC energy with the data already collected in 2010.

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